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Spacecraft Contamination Experience

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Contaminant

This definition for contaminant is very broad and could include items such as radio frequency, other forms of electromagnetic irradiation, particulate irradiation, meteoroids and debris, and atmospheric effects including atomic oxygen as well as the molecular and particulate materials that are usually considered.

The primary concern in this presentation is the molecular and particulate material that affects spacecraft system performance as a result of deposition on surfaces or being in the field of view of sensors. The contamination of sealed, internal fluid systems, gas and liquid, is not included because these subsystems are governed by well established standards and procedures. Exceptions to this are the deliberate introduction of material into the environment such as occurs during the operation of propulsion, evaporation, and other fluid systems that vent. Another area of concern is the unintentional leaking of contaminants into the environment.

It is important to consider contaminants that can deposit on spacecraft throughout the life of the hardware, from factory to the end of mission life. Spacecraft hardware may be exposed to ground environments for many years before exposure to the flight environments.

The contaminants that affect spacecraft systems are deliberately and accidentally put in or on spacecraft hardware and then can interact with the space environment even when these contaminants are added during ground environment exposures. A contaminant for one system or component may be a necessity for another. An example is the lubricant required in a bearing but that would degrade the performance of an optical system. Other examples include materials that contain molecular species that improve the processing or performance but outgas excessively.

Contamination Control

The process of achieving the required cleanliness levels requires a contamination control program that starts during the preliminary design phase and continues through to the end of mission life.

DEFINITIONS

Contaminant:

Any material, substance, or energy which is unwanted or adversely affects components and systems.

Contamination Control:

The planning, organization, and implementation of all activities needed to determine, achieve, and maintain a required cleanliness level.

Particle

Particles may be either solid or liquid. Airborne particles (aerosols) are usually small solid and liquid particles. The sizes of particles that can be carried in the air and their settling rates depend upon factors such as the particle density, shape (drag), and air velocity. Typically particles under 5 μm in size stay airborne for long periods of time, and particles over a few hundred μm in size settle out quickly.

Molecular Contaminant

Non-particulate matter (solid, liquid, or gas) has no definite shape and may exist on surfaces as uniform or non-uniform films. These contaminants may also be found as sorbed (absorbed and adsorbed) matter. The materials may also change state between solid, liquid, and gas. Particles may also change state, depending upon temperature and pressure, as well as changing to a molecular form.

NVR

NVR is usually considered to be a molecular contaminant that is found on surfaces or in liquids after evaporation of the liquid. Various test procedures are used to measure the NVR on spacecraft surfaces or on plates exposed to the ground environments. MIL-STD-1246 and NASA SN-C-0005 define NVR levels for hardware that have been in general use; however, other definitions are also used depending upon the requirements.

DEFINITIONS

Particle (Particulate Matter)

Matter of miniature size with observable, length, width, and thickness

Molecular Contaminant

Non-particulate matter, may be in a solid, liquid, or gaseous state

NVR (Non-Volatile Residue)

Soluble material remaining after the evaporation of a volatile liquid or determined by special purpose analytical instruments.

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INTRODUCTION

Effective contamination control must encompass all aspects of ground and flight from design of the system through the end of mission life.

Therefore,
Contamination control is a systems engineering function,

and,
a review of experience with space systems should include phases of activity from design to the end of life.

Contamination control activities should start during the preliminary design phase of a project. This includes the initial selection of materials and preliminary analyses of the sensitivities to contamination and quantities of contaminants. If the contamination control work is delayed, required design changes will increase costs, cause schedule delays, or compromise system performance.

DESIGN 1

It is necessary to include contamination control in the design trade off studies and to initiate operational planning activities that affect the design.

Each design activity has an impact on the contamination control program and there are iterative processes that contribute to the development of the design.

The determination of system performance requirements leads to a definition of the sensitivity of the system to contaminants.

The configuration of the system defines the relationship between the elements that are sensitive to contamination and the sources of contamination. This configuration can be changed to eliminate or, at least, minimize the contamination. The sources of contaminants include materials and components on the surface of the spacecraft as well as materials and components inside the spacecraft that get out through intentional and unintentional vents. The locations of these vents arefrequently a critical factor in the contamination of sensitive components.

The configuration also has a bearing on how easy or difficult it is to clean sensitive elements during the various phases of ground operations.

The selection of the materials, components, and subsystems so as to minimize outgassing and generation of particles involves tradeoffs with the need to meet the other functional requirements. These other functional requirements include temperature and radiation stability, mechanical and electrical properties, and resistance to atomic oxygen.

As the design develops it is possible to consider preliminary planning for ground and flight operations including those procedures that will minimize contamination. In this way design changes can be implemented early.

DESIGN 2

Activity	*Impact on Contamination Control*
Determination of Performance Requirements	**Defines system sensitivities**
Definition of Configuration	**Defines relationship between sensitive elements and sources of contamination**
	Ease of cleaning and protection
Selection of Materials, Components, Subsystems	**Affects outgassing, particle, generation, and other functions**
Planning of Operations for Factory, Launch Site, and Flight	**Affects the ability to meet requirements and minimize cost**

The contamination analyses are used to determine if the materials, components, and subsystems can be expected to meet the performance requirements for the system. When the analyses are performed early in the design process it is possible to make necessary changes with a minimum impact on schedule and cost. As the design develops, the analyses can be "fine tuned" for critical items.

The contamination control plan is a summary of the requirements and the procedures to be used to meet these requirements. The contamination control plan should start early in the design phase of a project. There may be many unresolved issues and blanks in the plan, but these indicate work that must be accomplished and to allow schedules to be set for implementation. One important purpose of the contamination control plan is to assure that the requirements and procedures are implemented in the working documents. It also allows all parties to review it and reach a consensus on the approaches to be followed starting early in the design activity.

Development tests should be used to get data that are needed in the design of the new space system. Typical development tests include outgassing tests on materials and components where there is a lack of data in the literature or special test conditions are required.

DESIGN 3

Activity	*Impact on Contamination Control*
Perform Contamination Analyses	**Determines if the configuration, materials, components, and subsystems that are used are likely to result in the cleanliness levels needed to meet system performance requirements.**
Prepare a Contamination Control Plan	**Summarizes the requirements, goals, and procedures and is used to provide guidance to all activities that impact contamination control.**
Perform Development Tests	**Tests should be performed early enough to affect designs without increasing costs.**

It is important to clean the hardware as it goes through the factory operations. It is especially critical to remove all oils and chips following machining, drilling, forming, and similar manufacturing operations. It is critical because particulate and molecular contaminants become trapped in enclosed (but not sealed) areas and can be released by exposure to the vibro-acoustic, vacuum, and elevated temperature environments during flight.

During the assembly operations, particles, debris, and oils should be removed before areas are closed out because it may not be possible to inspect or clean these areas again.

Many areas on a spacecraft are inaccessible even when they are not enclosed. The possibility of damaging sensitive components by performing cleaning operations late in the assembly phase may outweigh the benefits of the cleaning.

Spraying operations are particularly hazardous. Oils, paints, and solvents are frequently sprayed. Aerosols from spraying operations can be carried over long distances because the aerosols are very small, usually less than 1 μm in size.

Areas where spacecraft and components are tested have not always been cleanrooms; however, the current trend is to build new facilities, or modify old ones, to be cleanrooms. This makes the contamination control process much easier.

FACTORY OPERATIONS

Manufacturing

- **Clean hardware to remove oils and chips before assembling.**
- **Clean and protect hardware through all operations.**

Assembly

- **Clean areas that are being closed out.**
- **Protect the hardware.**
  - **There may be no way to access areas for inspection and cleaning.**

Test

- **Test areas should be clean facilities**
  - **Vibro-Acoustic, Thermal, Thermal-Vacuum**

Thermal-vacuum tests have frequently been a cause of contamination. There has been a tendency to blame the vacuum system for many of the problems; however, outgassing from the spacecraft and test equipment have been major causes of contamination.

The design of the chamber and vacuum pumping equipment is important, but the use of operating procedures that minimizes the probability for contamination are also necessary. The pumpdown, temperature changes, and return to one atmosphere are critical procedures for protecting the spacecraft from self contamination as well as contamination from the chamber and test equipment.

Equipment failures and accidents have also caused actual or possible contamination problems. Equipment should be fail-safe so that damage can not occur as a result of a failure. Typical problems have been electrical power and cooling water failures. When vacuum pumps fail or overheat contamination is likely to occur if there is no automatic, controlled shut down and manual restart system.

Errors by personnel have also resulted in problems. Although it is not possible to prevent human errors it is possible to human-engineer a system to reduce the probability of error and to have fail-safe controls installed.

Even if it turns out that no actual contamination occurred as a result of an accident, the time spent investigating and analyzing the failure increases costs and schedule times.

THERMAL VACUUM TESTS 1

Problem	*Corrective Action*
Contamination from equipment	**Verify prior to test** **Proper design and procedures**
Self contamination	**Proper operating procedures** **Monitor contamination**
Equipment failure & personnel error	**Design should be "fail safe"** **Proper operating procedures**
Power & cooling water **Pump failure** **Accident**	

Many measurements and tests can be performed during the thermal vacuum test to enhance the confidence and reliability of a system. These include the measurement of outgassing rates, the measurement of contaminant deposition and effects, and evaluation of performance under simulated flight conditions.

Outgassing rates and contaminant deposition from the Inertial Upper Stage (IUS) were measured during the thermal vacuum test program at the Boeing Company. The data were compared with the results of the contamination analyses and were used to improve the models and assumptions used in the analyses.

Outgassing rates from typical electronic boxes used on the Centaur upper stage were measured at the NASA White Sands Test Facility. The results were used to determine if the outgassing exceeded the predicted maximum allowable rates, based on contamination levels predicted from the contamination analyses. From the test results it was determined that the boxes should be subjected to a vacuum bakeout to reduce outgassing rates to acceptable levels.

There have also been many instances where contamination problems were encountered during thermal vacuum tests, and corrective actions were taken prior to flight. There have also been situations where problems were encountered but not corrected before flight, often because the cause was not understood.

THERMAL VACUUM TESTS 2

Activities to Enhance Confidence and Reliability

Measure Outgassing of Equipment and Spacecraft

- **Compare with the values used in the contamination analyses**

Look for Potential Flight Problems

- **Evaluate the performance under simulated flight conditions**

Facilities for handling space systems do not always get adequate attention in comparison with the hardware which go through these facilities. The state of the art with respect to contamination control has shown a great advance since the design and construction of the older, existing facilities. Also, the cleanliness requirements for spacecraft have become more demanding. The microelectronics industry has been forced to go to Class 10 and Class 1 cleanrooms, with commensurate improvements in procedures, as solid state devices have become smaller and more sensitive to smaller particles.

Although spacecraft do not require the degree of contamination control that is necessary for the fabrication of electronic and optical devices, the technology that has been developed in areas such as air filtration, measurement, garments, procedures, and facility construction are applicable to spacecraft facilities. Greater thought in the design and planning of these facilities is necessary to protect the expensive space hardware being produced.

It appears to be cost effective to design the protection and controls into a facility that is commensurate with the cost of the hardware and cost of schedule slips.

FACILITIES

The cost of building and launching space systems is expensive. Damage, failures, and delays can result in significant cost increases. Therefore, it is cost effective to design and construct facilities that minimize operating costs and provide fail-safe protection.

Some Problems That Have Been Observed

Overhead water pipe breaks over a long, holiday weekend and is discovered by a guard when water is seen leaking under a wall.

Overhead fire sprinkler system leaks or is turned on accidentally.

Local fire generates smoke with the potential for contaminating other hardware in the room, and the local sprinkler sprays water on some hardware.

Air conditioning system ingests outside contaminants.

Oil vapor leaks in from adjacent machine shop.

Corrossive vapor from adjacent metal processing room.

Delays at the launch site are especially costly because all elements of payload-launch vehicle system are affected even when only one of the elements has a problem. All elements must wait for the problems to be resolved. This ties up personnel and facilities.

The Tracking and Data Relay Satellite (TDRS) on Shuttle flight STS-6 experienced a number of problems. These problems included facility and procedural failures.

LAUNCH SITE OPERATIONS 1

Problems during launch site operations have a greater impact on cost and performance than those during factory operations.

Example: TDRS (Tracking and Data Relay Satellite) on STS-6

Problems:

High winds breached the seals resulting in the ingestion of contaminants into the Payload Changeout Room (PCR).

Installation work on the forward bulkhead of the Orbiter resulted in particulate fallout on to the TDRS.

Examples of some contamination problems occurred with the TDRS on STS-6. One event was the breach of the seals between the Orbiter and the PCR during high winds in a storm. Although this was potentially a serious event, analyses of the data showed that the airborne particle counts exceeded Class 100,000 only one time during the storm. Class 100,000, as defined by FED-STD-209, means that there are 100,000 particles per cubic foot of air of sizes 0.5 μm and larger. A Class 100,000 cleanroom must never exceed Class 100,000 during normal operations. The HEPA (High Efficiency Particulate Air) filters provide better than Class 100 air into the facility, and cleanrooms can be expected to have a Class 10,000 or better environment during normal operations; therefore, Class 100,000, although the maximum allowable, is considered very high for a cleanroom.

As a result of the TDRS event and greater concerns for contamination control at NASA KSC, considerable improvements have been made in facilities and procedures that have reduced the probability of similar problems in the future.

Another problem that occurred with STS-6 was the discovery of particulate contamination and debris on the TDRS. Some occurred when work was performed on the Orbiter forward bulkhead, above the TDRS, resulting in fallout. Some was found to have been on the TDRS previous to the Orbiter work and the storm. The procedures now reflect the need to protect the payloads when Orbiter work must be performed and require inspection of payloads before NASA will accept them into the launch site processing.

LAUNCH SITE OPERATIONS 2

TDRS on STS-6

Conclusions:

Significant particulate contaminants were observed on the TDRS prior to the above events.

Airborne particle counts exceeded Class 100,000 only once during the high winds.

Cleaning in place was limited because of possible damage to the spacecraft, and return to the factory was a major impact to the program.

Corrective Actions:

Clean TDRS as well as possible under the circumstances because the risk from contamination was low.

Improvements in facilities and procedures were started at KSC.

The launch and ascent environments potentially are the greatest contamination hazard for exposed hardware. The vibro-acoustic environment will remove particles from Orbiter payload bay surfaces, or payload fairing surfaces on expendable launch vehicles. Payloads and airborne support equipment will also be sources of particles during ascent. The turbulent flow of venting gases and the vehicle acceleration will transport the particles, so it is important to consider the cleanliness and placement of all hardware within the bay or payload fairing relative to the contamination sensitive components.

Venting of gases from within hardware may also carry molecular contaminants to sensitive components, and aerodynamic heating will increase the outgassing rates from payload fairing materials.

The payload fairing used on the Titan IIIC used a low outgassing RTV to seal particulate contaminants within the faying surfaces;, however, it is better to eliminate all contaminants from faying surfaces of structures during manufacture to significantly reduce problems during ascent.

Separation and deployment operations use thrusters, explosive devices, and mechanical elements. These generally produce molecular and particulate contaminants.

Measurements, using a QCM (quartz crystal microbalance), on the P74-1 mission on a Titan IIIC showed approximately 4 $\mu g/cm^2$ deposition in the payload area from the solid propellant retromotor on Stage 2.

LAUNCH AND ASCENT

The vibro-acoustic environment during ascent will remove particles from surfaces.

- **Orbiter payload bay**
- **Spacecraft, experiments, and airborne support equipment**
- **Payload fairing on expendable launch vehicles**

Aerodynamic heating may increase outgassing rates.

Separation and deployment activities produce molecular and particulate contaminants.

- **Separation techniques that use explosive devices and/or that cause materials to fracture**
- **Thruster operation**
- **Operation of mechanical elements**

Spacecraft in low Earth orbits are exposed to an ambient atmosphere that will affect the contaminant deposition and performance. Molecular contaminants that outgas or vent from the spacecraft can be scattered back to the spacecraft as a result of collisions with the atmosphere. This adds to the deposition from direct line of sight transport.

Solar ultraviolet irradiation will enhance contamination as a result of a photochemical deposition process.

Atomic oxygen will remove contaminants, such as hydrocarbons, that produce volatile species during oxidation. Contaminants, such as silicones, that produce solid oxides will remain. The net contaminant deposition, or removal, rate will depend upon the rates of each mechanism.

Spacecraft going to higher orbits will go into a transfer orbit. They may only spend a short time in low Earth orbit , so atmospheric effects may not be significant. There will be exposures to contaminants from additional thruster firings and separation activities.

Examples of contamination problems include the following:

Heat soaking back into the Kevlar-epoxy motor case on the IUS (Inertial Upper Stage) results in higher outgassing rates, and measures were taken to prevent the outgassing products from reaching sensitive components on spacecraft.

A contamination/collision avoidance (C/CAM) maneuver was designed for the separation of the spacecraft from the IUS to prevent outgassing products from the hot solid propellant motor from being emitted towards the spacecraft.

ORBITAL OPERATIONS 1

- **Low Earth Orbits**
  - **Long Exposure Times**
  - **Self-Contamination**
  - **Atmospheric Effects**
    - **Molecular back scatter increases molecular deposition.**
    - **Atomic oxygen will remove some molecular deposits.**
  - **Solar ultraviolet will enhance the molecular deposition**
  - **Micro-debris Impacts**
- **Transfer Orbits**
  - **Atmospheric Effects**
    - **This is usually a short exposure.**
  - **Venting and Outgassing**
  - **Thrusters**
  - **Separation**

As with most spacecraft contamination, the spacecraft is the primary source. Line of sight transport of molecular contaminants, directly from sources or reflection/emission from secondary surfaces, is the primary mechanism for contamination. Spacecraft electrostatic charging will also result in a return flux of molecular contaminants. This effect was predicted by analyses and then verified by the ML-12 experiment on the SCATHA (Spacecraft Charging at High Altitudes) spacecraft.

As in low altitude orbits, solar ultraviolet irradiation will enhance the deposition of molecular contaminants. This effect has been demonstrated on the ML-12 experiment and in laboratory experiments.

The electron and proton irradiation does not appear to have a large effect on contaminant deposition based on the ML-12 results. The QCM exposed only in the shadow of the spacecraft did not show the deposition that the QCM exposed to solar irradiation did.

ORBITAL OPERATIONS 2

High Earth Orbits

- **Long Exposure Times**
- **Self Contamination**
- **Spacecraft Charging**
  - **There is a return flux of charged molecular contaminants that originated from the spacecraft.**
- **Solar ultraviolet will enhance molecular deposition.**
- **The impact of electrons and protons on contaminant buildup is uncertain.**

Contamination data can be secured from two types of measurements in flight. One type is the experiment or measurement dedicated to contamination. The other involves the use of data from spacecraft housekeeping instruments or from some payload performing another mission related measurement.

Dedicated contamination instruments have flown on Skylab, Shuttle, Titan IIIC, LDEF (Long Duration Exposure Facility), SCATHA, NOAA-7, GPS (Global Positioning Satellite), DSP (Defense Support Program), and others. The instruments have included QCMs (quartz crystal microbalances), TQCMs (temperature controlled quartz crystal microbalances), calorimeters (ratio of solar absorptance to total hemispherical emittance), and radiometers.

The performances of spacecraft and components have also revealed the effects of contamination. Temperature measurements combined with analyses using thermal models of spacecraft have shown changes in solar absorptances and thermal emittances that have been traced back to contamination.

Data from optical sensors have also shown that contamination has affected performances, and analyses of solar array power output has shown evidence of contamination.

The problem with using data from spacecraft housekeeping, sensors, and power systems arises from the fact that there may be many things that affect performance besides contamination and the usually poor precision and accuracy of the measurement.

However, if more spacecraft flight data were analyzed, better contamination information useful for future design and operation would be available. Unfortunately, flight data usually is only analyzed when problems are encountered.

FLIGHT MEASUREMENTS 1

Dedicated Instruments

Skylab: QCMs, Solar Coronagraph

Shuttle: IECM (Induced Environment Contamination Monitor), NASA MSFC, on STS-2,3,4,9

CMP (Contamination Monitor Package), NASA GSFC, on STS-3

IOCM (Interim Operational Contamination Monitor), AFSD/JPL, on STS-51C

PACS (Particle Analysis Camera for Shuttle), AFGL, on STS-51C

Recoverable: LDEF

Expendable: QCM on P74-1 (Titan IIIC)

ML-12 on SCATHA

TQCM, calorimeter, & UV detector on NOAA-7

Calorimeters on GPS & DSP

Performance Analyses

Thermal analyses/Optical Sensor Changes/Electrical Power Analyses

Future contamination data in flight will come from the same type of measurements as in the past, dedicated instrumentation and analyses of the performance of spacecraft and payloads.

There are plans for instrumentation on Shuttle flights. The IOCM (Interim Operational Contamination Monitor) was developed by JPL for the Air Force Space Division and is planned to fly on future Shuttle flights. It consists of separate modules that can be attached to the sides of the Orbiter bay and contains both active and passive sensors. Data are recorded in flight and analyzed after the mission. Typical active sensors are TQCMs, radiometers, and calorimeters. Passive witness plates can also be flown on an IOCM module. The IOCM has the flexibility to incorporate new active sensors to perform special measurements.

The APM (Ascent Particle Monitor) was designed and built by Martin Marietta Aerospace for the Air Force Space Division. There are three modules that can be programmed to open and close during the ascent of the Shuttle Orbiter in order to capture particles in the bay. The particles will be counted and analyzed after the return of the Orbiter. The Aerospace Corporation Materials Sciences Laboratory is responsible for the experiment, and Rockwell International is responsible for Shuttle integration activities. The NASA Goddard Space Flight Center is providing significant support to the APM experiment. The first flight of the APM is now planned to be on STS-30, the Magellan Mission, scheduled for launch in April 1989.

NASA GSFC also has a Contamination Monitor Package (CMP) that has flown on STS-3, will fly on the EOIM-III (Effects of Oxygen Interaction with Materials) experiment, and could be available for future Shuttle flights.

The IBSS/SPAS (Infrared Background Signature Survey/Shuttle Pallet Satellite) experiment planned for a Shuttle flight will provide some data on contamination in the bay and during deployment and recovery.

Unfortunately there appear to be fewer opportunities for flights on spacecraft that are not recovered. The P-888 mission contains the IAPS (Ion Auxiliary Propulsion System) experiment sponsored by the NASA Lewis Research Center, The diagnostic instrumentation includes a QCM and solar cells that will provide general contamination data as well as data on deposition and effects of the mercury ion thrusters' effluents.

FLIGHT MEASUREMENTS 2

Some Planned Flights

Shuttle: **IOCM (Interim Operational Contamination Monitor)**

APM (Ascent Particle Monitor)

CMP (Contdamination Monitor Package)

Spacecraft: **IAPS (Ion Auxiliary Propulsion System) diagnostic instrumentation on P-888**

An effective contamination control program will contribute to reducing cost and meeting the performance requirements of a space system. One aspect of cost control is doing what is necessary to meet performance requirements but not doing more than is necessary.

The design phase of the project can be used to make the system less sensitive to contamination as well as making the system easier to clean and keep clean. Materials and components that contribute little or no molecular and particulate contaminants should be incorporated into the design at this time.

Facilities and procedures for manufacturing, assembly, test, and ground processing are critical for maintaining cleanliness. The importance of ground facilities as a part of space systems needs to be increased. For contamination control and the overall ground operations needs, the operating costs should be considered in the requirements on the design and construction of the facilities.

The ability to understand and predict contamination processes and effects depends upon knowing what is happening on spacecraft in flight. Greater use of contamination instrumentation and more analyses of performance for operational spacecraft are needed to develop the models for use in design and mission planning. Contamination experiments in flight and complementary laboratory experiments are needed to fill in the gaps and develop new technology for operational vehicles.

The use of standards and specifications will contribute to cost reduction by providing a uniform approach and quality of work and reducing duplication of effort. In addition to DoD and federal standards, committees within organizations such as the American Society for Testing and Materials (ASTM) and Institute of Environmental Sciences (IES) have been and will continue to play a major role in the development of standards. Greater support from DoD and NASA to the appropriate committees would help the effort.

CONCLUSIONS & ASSESSMENTS

The contamination control program must cover the project from the beginning to the end.

Design systems to minimize sensitivity to contamination, ease of cleaning, and contaminant production.

Facilities and procedures are critical to maintaining cleanliness during ground operations.

Flight operations should be planned so as to minimize contamination.

More data from flights are required to assess the adequacy of designs and operations.

Standards and specifications should include contamination control requirements.

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